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Photovoltaic Module Simulink Model for a Stand-alone PV System

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Abstract

Photovoltaic (PV) Module is indispensable of a stand-alone PV system. In this paper, a one-diode equivalent circuit-based versatile simulation model in the form of masked block PV module is proposed. By the model, it is allowed to estimate behavior of PV module with respect changes on irradiance intensity, ambient temperature and parameters of the PV module. In addition, the model is capable of function of Maximum Power Point Tracking (MPPT) which can be used in the dynamic simulation of stand-alone PV systems.

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Keywords: PV; MPPT; One-diode equivalent circuit

1. Introduction

Both research and technological development in the area of renewable energy sources are necessary to account for the increase in energy demand and environment problems in the world. Stand-alone photovoltaic systems are the best solutions such as communication system, water pumping and low power appliances in rural area. Such systems are consisting of a PV generator, energy storage devices, AC or DC consumers and elements for power conditions. PV module represents the fundamental power conversion unit of a PV generator system. The output characteristic of PV module depending on the irradiance intensity and the cell's temperature is nonlinear, so it is necessary to model it for the simulation of maximum power point tracking for stand-alone PV systems.

One of the objectives of the paper is a review of those existing methods and models. The main contribution of the paper is the implementation of a PV model in the form of masked block, and by the model the I-V characteristics of photovoltaic module with different combination can be simulated. On the other hand, the versatile model is capable of function of MPPT which is necessary in stand-alone PV systems.

2. PV generator

A PV generator is the whole assembly for solar cells, connections, protective parts, supports etc. In the present modeling, the focus is only on cell and module.

2.1 Solar cell

Solar cells are in fact large area semiconductor diodes. Due to photovoltaic effect energy of light (energy of photons) converts into electrical current.

The equivalent circuit for the simplest solar cell consists of diode and current source connected paralleling, as shown in Fig. 1(a) [1]. Current source current is directly proportional to the solar radiation and diode represents PN junction of a solar cell. Equation of ideal solar cell, which represents the ideal solar cell model, is:

$$I = I_{ph} - I_o \left[\exp\left(\frac{V}{AV_t}\right) - 1 \right] \quad (1)$$

Where:

“ I_{ph} ” is photocurrent (A);

“ I_o ” is reverse saturation current(A);

“ V ” is diode voltage(V);

“ V_t ” is thermal voltage, $V_t = 27.5$ mV at 25°C

“ A ” is diode ideality factor.

On the other hand, Thermal voltage can be calculated in the following equation:

$$V_t = \frac{kT}{q} \quad (2)$$

Where:

“ k ” is Boltzmann constant, $1.38 \times 10^{-23} \text{ J/K}$;

“ T ” is solar cell temperature (K);

“ q ” is charge of electron, $1.6 \times 10^{-19} \text{ C}$.

The solar cell temperature, as in (2) is described as [2]:

$$T = 3.12 + 0.25 G/G_{ref} + 0.899 T_a - 1.3 W_s + 273 \quad (3)$$

Where:

“ G ” is irradiance intensity (W/m^2);

“ G_{ref} ” is reference irradiance intensity, 1000 W/m^2 ;

“ T_a ” is ambient temperature;

“ W_s ” is local wind speed (m/s).

The photocurrent (I_{ph}) in (1) depends on irradiance intensity and cell temperature, which is described as:

$$I_{ph} = \frac{G}{G_{ref}} [I_{sc,ref} + \mu_{I_{sc}} (T - T_{ref})] \quad (4)$$

Where:

“ $I_{sc,ref}$ ” is solar cell short-circuit current at reference condition ($G_{ref} = 1000 \text{ W/m}^2$, $T_{ref} = 25^\circ\text{C}$, Air-Mass = 1.5);

“ $\mu_{I_{sc}}$ ” is the solar cell short-circuit temperature coefficient.

On the other hand, the cell's reverse saturation current is described as:

$$I_o = I_{o,ref} \left(\frac{T}{T_{ref}} \right)^{\frac{3}{A}} \exp \left[q E_g \left(1/T_{ref} - 1/T \right) / kA \right] \quad (5)$$

$$I_{o,ref} = I_{sc,ref} / \left[\exp \left(V_{oc,ref} / A V_t \right) - 1 \right] \quad (6)$$

Where:

“ $V_{oc,ref}$ ” is solar cell open-circuit voltage at reference condition;

“ E_g ” is band-gap energy in the solar cell, (1.12-1.15eV).

When a series resistance (R_s) is included, the equivalent circuit is the four parameter model, as shown in Fig.1(b)[3]. The I-V characteristic equation of a solar cell can be described as[4]:

$$I = I_{ph} - I_o \left[\exp \left(\frac{V + IR_s}{A V_t} \right) - 1 \right] \quad (7)$$

A modification to four parameter equivalent circuit is accomplished by adding a shunt resistor (R_{sh}) in parallel with the diode resulting in the five parameter model, as shown in Fig.1(c). The voltage-current characteristic equation of a solar cell is given as:

$$I = I_{ph} - I_o \left[\exp \left(\frac{V + IR_s}{A V_t} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (8)$$

Single solar cell's voltage is too minor to be in real operation, so module is shaped of a group of solar cells in series and parallel, with their protection devices.

2.2 Module

Current-voltage characteristic equation of equivalent circuit for the Photovoltaic module arranged in N_p parallel and N_s series can be described as [5]:

$$I^M = N_p I_{ph} - N_p I_o \left[\exp \left(\frac{V^M / N_s + I^M R_s / N_p}{A V_t} \right) - 1 \right] - \frac{(N_p / N_s) V^M + I^M R_s}{R_{sh}} \quad (9)$$

Where:

“ N_p ” is cells parallel number;

“ N_s ” is cells series number.

2.3 Newton-Raphson Method

As can be seen, the inclusion of a series resistance makes the solution for current a recurrent equation. One initially applied simple iterative technique only converged for positive currents, but Newton-Raphson method used converges much more rapidly, and for both positive and negative currents [6]-[7].

Equation (7) is also described as:

$$I_{ph} - I_o \left[\exp \left(\frac{V + IR_s}{A V_t} \right) - 1 \right] - I = 0 \quad (10)$$

$$\text{Then, } f(I) = I_{ph} - I_o \left[\exp \left(\frac{V + IR_s}{A V_t} \right) - 1 \right] - I \quad (11)$$

Solution to current with Newton-Raphson method can be described as:

$$I_{K+1} = I_K - \frac{f(I_K)}{f'(I_K)} \quad (12)$$

Where:

“ I_K ” is K th iterative current;

“ I_{K+1} ” is $(K+1)$ th iterative current.

It is well known that PV module power equals to value that voltage multiplies current, and can be described as:

$$P = I^M \cdot V^M \quad (13)$$

On the other hand, solution to voltage at maximum power point (MPP) for PV module with Newton-Raphson method can be described as:

$$V_{K+1}^M = V_K^M - \frac{P'(V_K^M)}{P''(V_K^M)} \quad (14)$$

Where:

“ V_K ” is K th iterative voltage at MPP;

“ V_{K+1} ” is $(K+1)$ th iterative voltage at MPP.

3 PV model building and simulation

The Matlab/Simulink model of PV module illustrates and verifies the nonlinear voltage-current and power-voltage output characteristics of an arbitrary module using a one-diode equivalent circuit. In addition to that, the model includes the function of Maximum Power Point Tracking (MPPT). Model inputs are the irradiance intensity and ambient temperature. The subsystems for proposed model are implemented and shown in Figs.2 (a), (b) and (c). The masked model is design to have a dialog box as show in Fig.3, in which the parameters of PV module can be configured in the same way.

4 Results and Conclusion

The Solarex MSX60 PV module is taken for example, which provides 60 watt of nominal maximum power, and has 36 series connected polycrystalline silicon cells. The key specifications are listed in Table I [8].

The parameters that determine the operation of PV module are reflected in their characteristic curves, I-V and P-V. For the calculation of two families of curves, first the cell's working temperature stayed constant at 298K generating a type of curves for irradiance intensity (1000, 750, 500 and 250W/m²). Later, irradiance intensity maintains constant at 1000W/m² calculating the curve for 273, 298, 323 and 348K. Both I-V and P-V output characteristics of MSX60 PV module at various solar irradiance intensity and temperature are carried out and the results are shown in Figs.4-5. It can be seen from Figs.4 (a) and (b) that with increase of the cell's working temperature, the short-circuit current of the PV module increases, whereas the maximum power output decreases. On the other hand, with the increase of irradiance intensity, the short-circuit current and the maximum power outputs increase as shown in Figs.5(a)and(b),and in which it is also shown that current is proportional to irradiance intensity and open-circuit voltage is logarithmically dependent on the solar irradiance.

On the other hand, the effect varying with the ideality factor is shown in Fig.6- higher values soften the knee of the curve. The series resistance of the module has large impact on the slope of the I-V curves at open-circuit voltage as seen in Fig.7.

The main contribution of the paper is the implementation of a PV model in the form of masked block, and by the model that predicts the electrical output of an arbitrary module using a one-diode equivalent circuit or a maximum power point tracking (MPPT) circuit connected to the module the I-V characteristics of PV module with different combination can be simulated.

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TABLE I. TYPICAL ELECTRIC CHARACTERISTIC

Parameter	Variable	value
Maximum Power	P_m	60 W
Voltage@ P_m	V_{mp}	17.1 V
Current@ P_m	I_{mp}	3.5 A
Open-circuit Voltage	V_{oc}	21.1 V
Short-circuit Current	I_{sc}	3.8 A
Temperature Coefficient of Short-circuit Current	$\mu_{I_{sc}}$	$(0.065 \pm 0.015) \%/^{\circ}\text{C}$

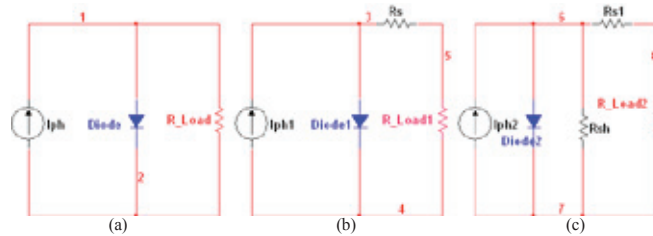
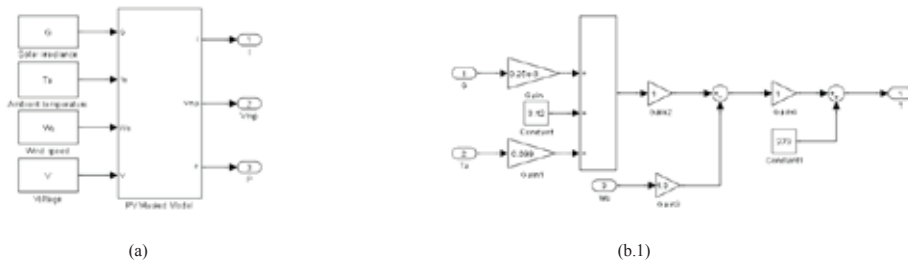
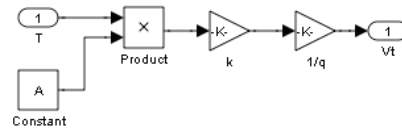
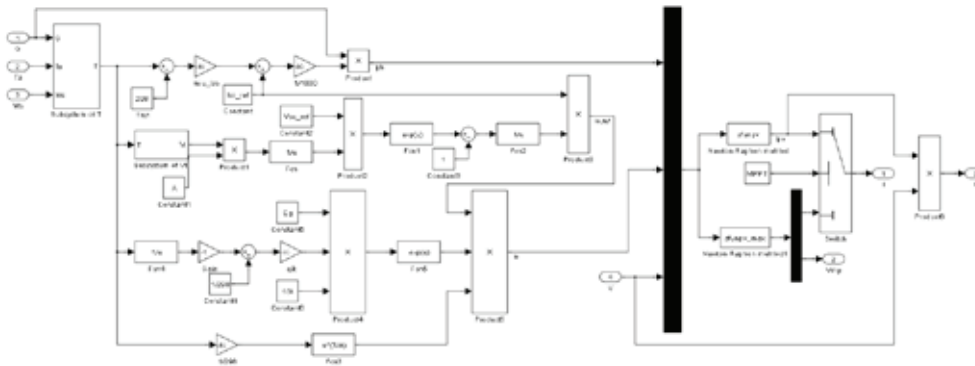


Figure 1. Three Equivalent circuits for solar cell





(b.2)



(c)

Figure 2. Building: (a)Masked implementation of PV model;(b)Subsystem implementation of T and Vt; (c)Subsystem implementation of PV mode

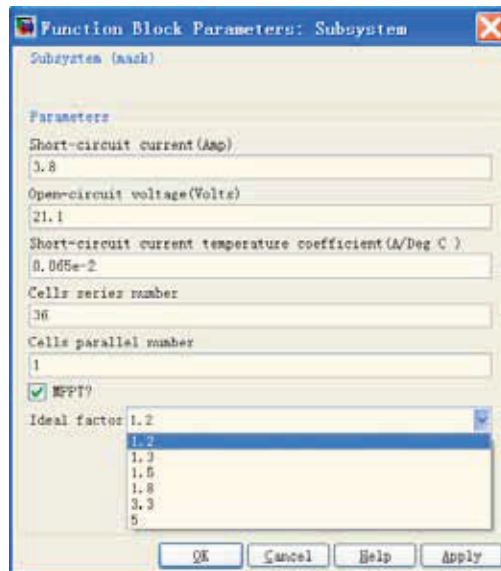


Figure 3. Dialog box of PV model

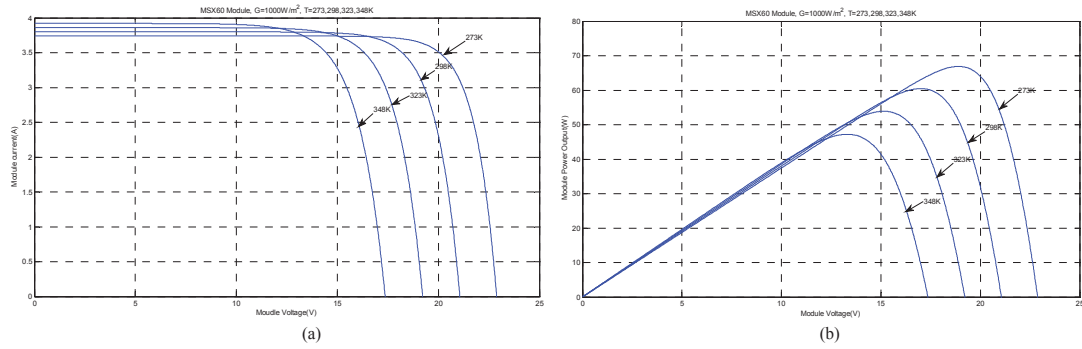


Figure 4. Characteristics with different T: (a)I-V output characteristic; (b)P-V output characteristic

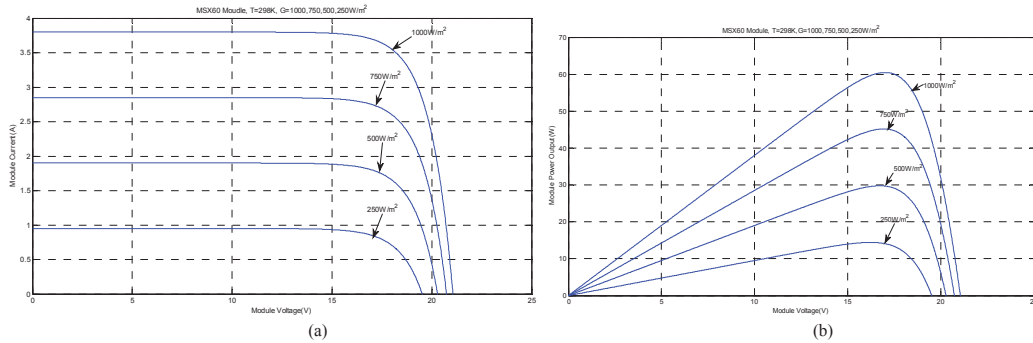


Figure 5. Characteristics with different G: (a)I-V output characteristic; (b)P-V output characteristic

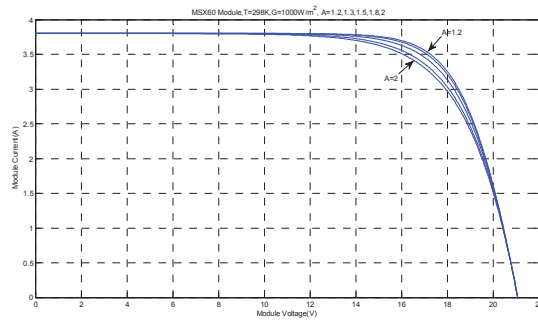


Figure 6. Effect of diode ideality factor ($G=1000 \text{ W/m}^2$, $T=298 \text{ K}$)

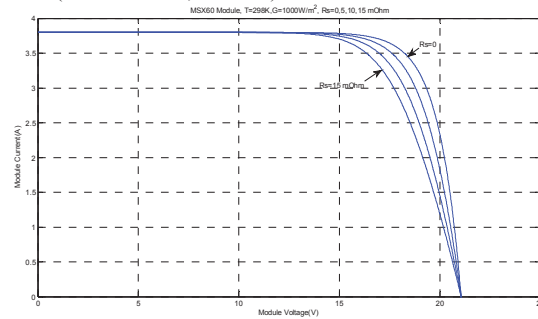


Figure 7. Effect of series resistances ($G=1000 \text{ W/m}^2$, $T=298 \text{ K}$)